Solar Flare Imaging in X-rays and γ-rays

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Abstract.

Recent results of solar flare imaging at X-ray and γ-ray energies are briefly summarize using observations from the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) Small Explorer mission.

Index Terms. particle acceleration, solar flares, X-ray and Gamma-ray emission

1. Introduction

The Sun is the most energetic particle accelerator in the solar system, producing ions up to tens of GeV and electrons to hundreds of MeV in solar flares and in fast coronal mass ejections. Solar flares are the most powerful explosions, releasing up to 1e32-1e33 ergs in ~10-1000~s. The flare-accelerated ~20-100 keV electrons (and sometimes >1 MeV/nucleon ions) appear to contain a significant fraction, ~10-50%, of this energy, indicating that the particle acceleration and energy release processes are intimately linked.

X-ray and γ-ray emissions are the most direct signature of the acceleration of electrons, protons and heavier ions in solar flares. Bursts of bremsstrahlung hard X-rays (HXR) emitted by accelerated electrons colliding with the ambient solar atmosphere, are the most common signature of the impulsive phase of a solar flare. Collisions of accelerated ions with the atmosphere result in a complex spectrum of narrow and broad γ-ray lines. Furthermore, hot (multi-million Kelvin) thermal flare plasmas also emit bremsstrahlung X-rays. Hence, X-ray and γ-ray observations are excellent diagnostics of flare accelerated energetic particles and flare heating.

This short review focuses on recent results provided by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) mission (Lin et al. 2002). The primary scientific objective of RHESSI Small Explorer mission is to investigate the physics of particle acceleration and energy release in solar flares, through imaging and spectroscopy of X-ray/γ-ray continuum and γ-ray lines emitted by accelerated electrons and ions, respectively. It provides the first hard X-ray imaging spectroscopy, the first high resolution spectroscopy of solar γ-ray lines, and the first imaging of solar γ-ray lines and continuum. Here we briefly summarize some of the recent results only discussing flare imaging. More complete reviews of recent results can be found in Hudson et al. 2004 and Dennis, Hudson, & Krucker 2006.

2. Imaging in X-rays (electrons)

Hard X-ray (HXR) observations are a powerful diagnostic tool providing quantitative measurements of non-thermal electron beams accelerated in solar flares. Energetic electrons in a plasma radiate HXR emission through the well known process of bremsstrahlung. Since bremsstrahlung emission depends on the density of the ambient medium, solar HXR emission is largest below the transition region where the density increases exponentially towards the photosphere. Electron beams entering the chromosphere lose energy quickly through collisions producing relatively intense HXR emission at the footpoints of magnetic field lines. Electron beams moving in the relatively tenuous corona suffer only a few collisions and do not lose a significant amount of energy, but also produce only faint HXR emission. Present-day instrumentation does not have the dynamic range or the sensitivity to see faint HXR emission from electron beams moving in the corona next to bright HXR footpoint emissions in the chromosphere. Existing observations therefore show us only where energetic electrons are stopped but not along what path they escape from the acceleration site. X-ray observations (Figure 1) indeed show that flare accelerated energetic electrons are seen to lose their energy primarily in footpoints of magnetic loops (but also see Veronig & Brown 2004). Almost all of the energy lost in the collisions will heat chromospheric plasma. Evaporation of the heated chromospheric plasma is then filling the flare loop that is seen in thermal X-rays (Figure 1).

Magnetic reconnection is presently the most discussed theory to explain solar flares. During the last decade, indirect evidence for the magnetic reconnection scenario were reported mostly using X-ray observations from the Yohkoh spacecraft: cusp-shaped soft X-ray flare loops (Tsuneta et al. 1992; Tsuneta 1996), an increase of loop height and footpoint separation with time (Tsuneta et al. 1992), high-temperature plasma along the field lines mapping to the tip of the cusp (Tsuneta 1996), a hard X-ray source located above the soft X-ray loops (Masuda et al. 1994), horizontal inflow above the cusp region (Yokoyama et al. 2001), downflow above the cusp-shaped loops (McKenzie & Hudson 1999), and an upward-ejected plasmoid above the loops (Shibata et al. 1995; Ohyama & Shibata 1998). Compared to Yohkoh, RHESSI provides better spatial resolution, better dynamic range, much better spectral resolution, and observations in the γ-ray range.

2.2 HXR footpoint motion

Standard magnetic reconnection models predict increasing separation of the footpoints during flares (e.g., Priest and Forbes 2002) as longer and larger loops are produced. If the reconnection process results in accelerated electrons (Oieroset et al. 2002), then the HXR footpoints should show this motion. The motion is only apparent; it is due to the HXR emission shifting to footpoints of neighboring newly reconnected field lines. Hence, the speed of footpoint separation reflects the rate of magnetic reconnection and should be roughly proportional to the total HXR emission from the footpoints. Sakao, Kosugi, & Masuda (1998) analyzed footpoint motions in 14 flares observed by Yohkoh HXT, but did not find a clear correlation between the footpoint separation speed and the HXR flux. Recently, however, source motion seen in Hα was studied by Qiu et al. (2002). They found some correlation with HXR flux during the main peak, but not before or after. RHESSI observations partly confirm this picture, but footpoint motions are often found to be more complex than the simple two dimensional reconnection models (Fletcher & Hudson 2002; Krucker, Hurford, & Lin 2003). For some events, the HXR source motion is found to be correlated with the total released energy in energetic electrons (Krucker, Hurford, & Lin 2003; Krucker, Fivian, & Lin 2005). This is consistent with magnetic reconnection if a higher rate of reconnection of field lines (resulting in a higher footpoint speed) produces more energetic electrons per unit time and therefore more HXR emission. In other events, however, footpoint motions are observed to move along the flare ribbons and not perpendicular to it, as predicted by simple reconnection models (Grigis & Benz 2005). The January 20, 2005 flare is an example of an event with HXR footpoint motion along the flare ribbons (Figure 2).

2.3 Coronal hard X-ray emissions

Sui & Holman (2003) analyzed a series of flares from the same active region showing cusp shaped flare loops (Figure 3, left). During the impulsive phase of the flare, the cusp part of the coronal source separates from the underlying flare loop. This is interpreted as the start of the reconnection when a Y-type magnetic configuration is formed (Priest & Forbes 2002). The temperature of the underlying loops increases toward higher altitudes, while the temperature of the separated source increases toward lower altitudes indicating that the hottest temperatures are observed in-between (Figure 3, left). This temperature gradient might indicate that a current sheet is formed between the top of the flare loops and the coronal source with the hottest temperatures being closest to the current sheet.

Coronal X-ray emissions are most often from hot thermal loops as described above. For some events, however, an additional hard X-ray source is observed during the impulsive phase of the flare originating above the thermal X-ray loops (Masuda et al. 1994). Therefore, this source is called 'above the loop top source' (ALT source). ALT sources are first observed by Yohkoh, but only seen in a few flares. These sources are generally fainter with a softer (steeper) spectrum than the X-ray footpoint sources making it difficult to observe them next to the much brighter HXR footpoints. Their interpretation is not understood. If the footpoints and the ALT source are all produced by the same population of energetic electrons, the location of the ALT source indicates that the acceleration does not happen inside the flare loop but above. Therefore, it is generally speculated that the acceleration occurs above the thermal flare loops. This is further supported by timing arguments (Aschwanden et al. 1996).

An example of RHESSI observations of an ALT is shown in Figure 3 (middle). The HXR footpoints for this event are occulted by the solar limb, making it possible to detect the much fainter ALT source (blue contours) seen above 20 keV. The temporal evolution of the ALT source shows several peaks varying on time scales of tens of seconds and is clearly different from the thermal source (red contours) that shows a gradual rise during the same time period. The spectral variations show a so-called 'soft-hard-soft' behavior (i.e. the spectrum is flatter (harder) during the peak than in-between peaks) as generally seen in HXR footpoints (Grigis & Benz 2004). The observed spectra are rather soft (steep) and are slightly better represented by non-thermal spectra than by thermal fits, although multi-thermal fits with temperatures up to ~100MK can represent the data almost as well. The fast time variations, however, are very difficult to explain for the thermal interpretation (i.e. repeated heating to 100 MK and cooling on the same time scale). However, there are also difficulties with the non-thermal interpretation: the HXR producing electrons in the ALT source should significantly heat the surrounding plasma, but the hot thermal loops are observed below it.

Next to ALT sources seen in the impulsive phase of flares, RHESSI discovered coronal HXR sources during the pre-impulsive phase of large solar flares (Lin et al. 2003). Figure 3 (right) shows a limb flare with a purely coronal source above 35 keV seen several minutes before the impulsive phase. These coronal emissions are also better represented by non-thermal spectra (Holman et al. 2003), a finding that is supported by radio observations (White et al. 2003). However, the deposited energy of the HXR producing electrons is very large, even larger than during the impulsive phase (Holman et al. 2003), questioning the non-thermal interpretation.

2.4 HXR emission and escaping electron beams

Some of the flare accelerated electrons lose their energy by collisions in the denser, lower solar atmosphere producing HXR emissions and heat the corona, while others escape into interplanetary space and are detected in-situ by spacecraft in the inner heliosphere (e.g. Lin 1985). Whether the HXR producing and the escaping electrons are accelerated by the same mechanism is not known. Combining RHESSI HXR observations with in-situ observations of energetic electrons from the WIND spacecraft (Lin et al. 1995) allows for the first time a detailed temporal, spatial, and spectral study. First results for events with a close temporal agreement between the HXR and the in-situ detected electrons (taking the time of flight of the escaping electrons into account) show a correlation between the HXR photon spectral index and the electron spectral index observed in-situ (Krucker et al.

2006) indicating a common acceleration mechanism. However, the derived number of escaping electrons is about two orders of magnitude smaller than the number of electrons seen to lose their energy in the HXR footpoints.

The X-ray source structures of these events look similar, showing hot loops with HXR footpoints plus an additional HXR source separated from the loop by ~15" (Figure 4, left). This source structure can be explained by a simple magnetic reconnection model with newly emerging flux tubes that reconnect with previously open field lines, so-called interchange reconnection (Figure 4, right). For all events with simultaneous TRACE observations, EUV jets are observed possibly outlining the direction of open field lines.

3. Imaging in γ-rays (ions)

The acceleration of ions to high energies in large solar flares has been established by the detection of nuclear γ-ray line emission. When energetic ions collide with the solar atmosphere, they produce excited nuclei that emit prompt nuclear de-excitation lines, as well as secondary neutrons and positrons that result in the delayed 2.223 MeV neutron-capture and 511 keV positron-annihilation line emissions. Spectral observations have provided information on the energy spectrum of the accelerated ions and on the composition of the ambient atmosphere and the accelerated ions. RHESSI provides for the first time imaging in the γ-ray range, the only direct indication of the spatial properties of accelerated ions near the Sun.

The most powerful tool for γ-ray imaging is the 2.2 MeV neutron capture line, because of good statistics and a narrow line width which limits the non-solar background to a minimum compared to broad lines. Nevertheless, only for the largest flares (large X-class flares that are generally two-ribbon flares) statistics are good enough to image the 2.2 MeV emissions. Only flare averaged images with spatial resolution of 35" can be derived (compared to 4 second cadence imaging at 2" scales in the X-ray range) with a limited dynamic range of typically below 3 (i.e. faint sources next to a bright source can only be detected if the faint source is at least one third of the brightness of the main source).

Hurford et al. (2003) reported single or double source structures in the 2.2 MeV emissions unresolved at the instrumental resolution excluding a large diffuse source. For the event with the best statistics (Figure 5), a double source structure is observed coinciding with the flare ribbons, i.e. γ-ray footpoints are observed. The separation of the two γ-ray footpoints is similar to the separation of the HXR footpoints, indicating that proton and ions are accelerated on similar sized loops. However, compared to the locations of the HXR footpoints, the 2.2 MeV centroids are displaced by ~15" indicating a different location where energetic electron and ions lose their energy. The displacement could be explained by different accelerator sites for electrons and ions and/or by different transport effects from a possibly common acceleration site to the location where the electrons and ions lose their energy by collisions. RHESSI γ-ray flares with lower statistics are consistent with the analysis of the October 28 flare, but show only a single source. This can be explained by the limited dynamic range (i.e. second source is weaker and is therefore not detected, as in January 20 flare; Figure 1) and/or the observed unresolved source contains emission from both ribbons. The separation of the γ-ray footpoints relative to the HXR footpoints is presently not understood.

4. Summary

Flare imaging in the X-ray and γ-ray range are briefly reviewed in the previous sections using RHESSI observations as examples. While here mainly beautiful pictures are shown, the reader is referred to Hudson et al. (2004) for a more complete review.

Fig. 1. Solar flare imaging in X-rays of two large X-class two ribbon flares: Thermal and non-thermal X-ray emissions are shown in red and blue contours, respectively. For the January 20, 2005 flare (left) the flare loop is seen mostly from the side, while for the October 28, 2003 flare that occurred near disk center the flare loops are seen from above. The underlying image shows TRACE observations outlining the flare ribbons. HXR footpoint emissions are typically seen only from some parts of the EUV ribbons, but not along the entire ribbons. The pink circle marks the flare averaged location of the 2.2 MeV line emission in the January 20 flare.

Fig. 2. Temporal evolution of HXR footpoint sources during the January 20, 2005 flare (06:43-06:48 UT). The motion in time of the strongest emission on each flare ribbon is indicated by arrows and increasing symbol size (cadence is of 20 seconds). Simultaneously brightening footpoints are connected by elongated semicircles outlining possible the flare loops. The motion of the northern footpoint is clearly along the ribbon, contrary to reconnection models that predict motion perpendicular to the ribbons.

Fig. 3. Example of coronal X-ray emissions from a flare as seen by RHESSI: (left) flare with thermal source above the main flare loop (after Sui & Holman 2003); (middle) HXR 'above the loop top source' in a partially occulted flare. The red contours show the thermal flare emission, the blue contours give the location of the ALT source. HXR footpoints are occulted by the solar limb and therefore not visible. (Right) coronal hard x-ray source seen before the impulsive phase of an X-class large flare.

Fig. 4. Solar source region of a flare releasing energetic electrons into interplanetary space that are later observed near Earth: (left) RHESSI X-ray contours at 6-12 keV (red, thermal emission) and 20-50 keV (blue; non-thermal emission) are overlaid on a TRACE 195A~EUV image (dark corresponds to enhanced emission). Around [700,-245], the X-ray emission clearly outlines a loop with two non-thermal footpoints. The strongest non-thermal source however, is slightly to the south east [683,-257] and surprisingly shows a lower intensity thermal source. (Right) Simple magnetic reconnection models (interchange reconnection) predict a similar source structure: The red gray box marks the acceleration site from where downward moving electrons produce the HXR sources and upwards moving electrons escape into interplanetary space. TRACE observation shows a EUV jet outlining the direction of open field lines.

Fig. 5. Imaging of the 2.2MeV neutron capture line and HXR electron bremsstrahlung emission of the October 28, 2003 flare. The event averaged 2.2 MeV centroid positions (pink circles) and the 100-200keV contours are superposed on a TRACE EUV 195A image. Both emissions are related to the flares ribbons seen in EUV, but are slightly (~15") shifted relative to each other. Thermal X-ray emissions of this flare are shown in Figure 1.

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